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Cooling strategy for effective automotive power trains: 3D thermal modeling and multi-faceted approach for integrating thermoelectric modules into proton exchange membrane fuel cell stack

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ABSTRACT

The 3D Thermal modeling utilizes a Finite Differencing heat alteration method augmented with empirical boundary conditions is employed to develop 3D thermal model for the integration of thermoelectric modules with proton exchange membrane fuel cell stack. Hardware-in-Loop was designed under pre-defined drive cycle to obtain fuel cell performance parameters along with anode and cathode gas flow-rates and surface temperatures. The fuel cell model is used to conjugate the experimental boundary conditions with the Finite Differencing code, which implemented heat generation across the stack to depict the chemical composition process. The structural and temporal temperature contours obtained from this model are in compliance with the actual recordings obtained from the infrared detector and thermocouples. The model is harmonized with thermo-electric modules with a modeling strategy, which enables optimize better temporal profile across the stack. This study presents the improvement of a 3D thermal model for proton exchange membrane fuel cell stack along with the interfaced thermo-electric module. The model provided a virtual environment using a model-based design approach to assist the design engineers to manipulate the design correction earlier in the process and eliminate the need for costly and time consuming prototypes.

Introduction

Among various fuel cell types, proton exchange membrane fuel cells (PEMFCs) are the most promising for automotive applications due to their higher power density and lower operating temperature. The PEMFCs are getting more attention due to improvement in performance and durability of catalysts and electrolyte [1]. The operating temperature of PEMFC's is <90 °C with air in cathode at relatively lower

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pressure leading to water formation. This leads to thermal and water management issues as water formed is in liquid state [1,2].

There has been an intensive research conducted in order to improve the performance of the PEM Fuel Cells. Setareh et al. developed 3D model that can be used for heat transfer rate design and cooling devices for PEMFC systems, and is validated for an air-cooled fuel cell stack [3]. This model was used to replicate the 3D temperature signature and estimate the maximum temperature in an air-cooled PEMFC stack. Authentic preliminary information of various tests was required in order to model the thermal and water transport. Special importance should be given in developing fuel cells for automotive applications which involve transient heat issues like start-up, shut down and freezing [4]. A 3D flow simulation was created by Shimpalee and Dutta [5] to study the numerical analysis of the flow channel. The results showed that the overall performance of fuel cell not only depends on inlet set-up conditions like membrane thickness, inlet flow rate but also temperature variation inside the fuel cell model. Nguyen et al. [6] proposed a two-dimensional heat and mass-transfer to gauge the effectiveness of various humidification strategies. The results showed that the anode gas stream must be humidified before letting into the fuel cell as the back diffusion of water is insufficient to maintain the membrane hydrated.

Computational Fluid Dynamics Analysis was intensively used in analyzing the thermo fluid aspect of the PEM Fuel Cell. For instance, Matian et al. [7] developed a computational model of the PEMFC to study the heat generated and distribution of heat of the surface of the model using thermal imaging cameras. The validated results showed that the temperature distribution in a stack is significantly influenced by stack composition and drawn power density.

Alternatively, Del Real et al. [8] provided key inputs to develop powerful model and validate the results through a dynamic system (for 1.2 KW NEXA) which is very commonly used by research groups. The main contribution was the unique way of obtaining polarization curves experimentally, and modifying the thermal equations for an air cooled stacks and model flooding event in the FC stack. Similarly, Khemili et al. [9] established a thermal model to investigate the temperature distribution in the PEMFC and evaluate the effect of the liquid water on this temperature deviation at high current density.

Djilali et al. [10] analyzed the integration of PEMFC models into multi-dimensional CFD codes and illustrated their application in plate and frame unit cells. Analyzing the performance of a fuel cell as a function of voltage–load current characteristics was conducted by Sharifi et al. [11], where two complete fuel cell models under steady-state and dynamic conditions were proposed. The results showed the transient phenomenon combined together simultaneously three prominent dynamic aspects like Temperature changes, Fluid flow and pressure changes through channels of double layers. Yi Zong et al. [12] proposed a non-isothermal and non-isobaric model with non-uniform stack temperature. The Model consisted several parts like mass balance, energy balance, pressure drop and cell output voltage. The mass balancing equations are used to calculate the energy balance equation and Newton–Raphson method is applied to calculate the local current density. Based on the simulation on both anode and cathode, it was found that the anode and cathode should supply with humidified fuel, to prevent the membrane from dehydrating.

A one-dimensional, steady state, isothermal fuel cell model was established by Bao et al. [13] focusing design methodology and analysis of water and thermal management of the fuel cell. More recently, Cao et al. [14] developed a three dimensional two phase, non-isothermal model of the PEMFC to perceive the interaction between water and heat transport, fluid flow of the model, electrochemical reaction and heat transfer process. Musio et al. [15] established a modeling access which was implemented in Matlab-Simulink context. The stack model was set up based on elementary equations for fluid dynamics, thermal dynamics and kinetic behavior of the system. A thermal control model for the system was progressed for an air cooling system which enabled in differentiating various heat removal techniques. Finite differencing (FD) have been used to understand the heat transfer mechanism. For example, Mayyas et al. [16] compounded a 3D model using FD heat transfer technique correlated with experimental boundary conditions for hybrid power train containing battery pack and power electronics. The model predicted the spatial and temporal temperature portrait in accord with the actual vehicle conditions. Similar, approach is used in this paper, but in this case the subject of study 3D fuel cell model.

In this study, a 3D thermal model is developed and validated to analyze and predict the thermal performance of air-cooled PEMFCs. The model is developed based on a multi-faceted approach; this combines both finite differencing code (FDC) and experimental boundary conditions obtained during an implementation of various simulated standard and artificial driving cycles. The fuel cell system was tested in Hardware In-the-loop (HiL) configuration. The HiL uses a complete model of FCV where the modeled fuel cell system was replaced with a real fuel system. This type of set up and configuration aimed to mimic the real-world loading scenarios. Air-cooled FC system serves two purposes, the cooling function and cathode flow which reduces the overall cost of auxiliary systems. A focal plane array infrared detector [7] is used in order to obtain 2D thermal maps for the FC stack mount surface. The thermal images from the infrared detector are used to validate the thermal signature of the FC stack mount surface by a comparison with the model output. In addition, the model has been integrated with the thermo electric module for optimizing the FC stack performance.

Experimental

This part provides the fundamental procedures and mechanisms required to establish a model and attain the required boundary conditions from an operating Fuel cell system (FC). This empirical work helps to get stack temperature, stack voltage, flow rates, net power and temperature distribution through the surface of the stack.

Fuel cell system

The experimental set up shown in Fig. 1 consists of NEXA 1.2 KW fuel cell stack (FC GEN 1020 from BALLARD) with

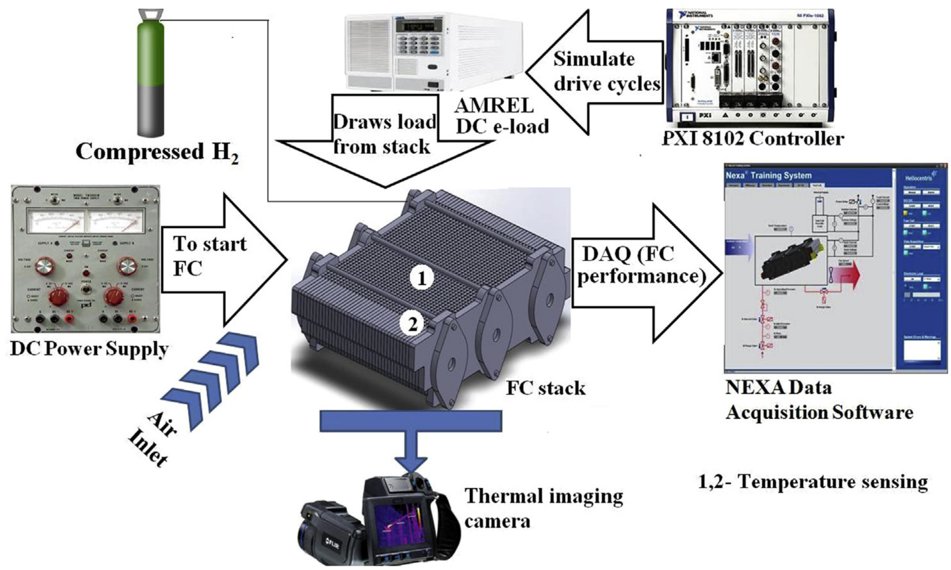

Fig. 1 – Schematic of the experimental set-up.

36 cells (obtained from Heliocentris), PXI 8102 controller, AMREL DC electronic load and forward looking focal plan array infrared T620 FLIR. The FC stack has advanced open cathode technology where the inlet air is utilized from the atmospheric air and also has self-humidifying membrane electrode assemblies (MEA) [17]. The stack is placed in tilted position to facilitate the air inlet and cooling the system. The PXI 8102 Controller functions as hardware-in-loop platform, which draws input from simulated FCV model. The PXI controller simulates the drive cycles through the AMREL (W PEL series 300-60-60) DC electronic load. The FC system is initiated using an external DC power supply unit (24 V, 1 A).

Fuel cell modeling, simulation and evaluation

The thermal performance of the 1.2 KW FC systems is surveyed under several transitory conditions for different power requirements, operating under different standard and user defined drive cycles. The entire FCV consisting of FC system is advanced using Simulink. The inputs for the Simulink model are the devised standard drive cycles. The input signals for the Simulink model includes three standard drive cycles Federal Urban Driving Schedule (FUDS), Federal Highway Driving Schedule (FHDS), US-06 (Aggressive urban) and Acceleration Driving Test (ADS). This mix of city, highway and aggressive driving patterns replicate a real-world driving condition. The speed profiles are fed to the Simulink model in real-time. The model and based on the torque command will dictate the power demand in real-time to force the DC power supply draw the necessary current from the fuel cell. These scenarios are more practical approach in studying the performance and analyzing the behavior of the fuel cell in HiL configuration.

The FC current, Flow rates and voltage are obtained for each standard drive cycle. The electric current and voltage of the fuel cell is scripted at one Hz based off the drive cycle with an in-built data acquisition system. The DAQ keeps a log of FC stack voltage, load current, FC temperature, operating pressure and ambient temperature at one Hz through various drive cycles. It is noted that there is always static current of 1.43 A drawn from the FC stack, this is the current drawn by the auxiliary electronic components.

The structural and terrestrial temperature contour for FC stack is documented for various drive schedules using an infrared detector. A FLIR T620 focal plane array FPA Thermal Imaging IR Camera was placed in front of the FC stack at a distance of about 1 m to capture the 2D superficial temperatures in real-time. The thermal camera has thermal resolution of 307,200 pixels, spectral range of 7.5–14 μm and a thermal sensitivity of <0.04 °C, detecting temperature range of −40 to 650 °C ± 2 °C accuracy. The camera is also equipped with Examin IR 1.40.2 real-time image/data logging and plotting software [18]. The thermocouple network (positions 1 and 2 as shown in Fig. 1) is positioned to detect the temperature divergence on the surface of stack. The thermocouples are critical as they complete the closed loop feedback system, transmitting signals to PXI controller.

The FC system assessment began at 23 °C, in a sequential manner with FHDS cycle simulated first, followed by FUDS, US-06 and at last ADS. This systematic approach of drive cycle simulation helps us to study the fuel cell in steady state condition in more meticulous manner. Federal Highway Drive Schedule (FHDS) and Federal Urban Drive Schedules (FUDS) represent drive cycles used by U.S. Environmental Protection Agency to validate that light duty vehicles fulfill the federal emissions and fuel economy standards. FHDS represents highway and rural driving with warmed-up conditions. FUDS replicates frequent stop-and-go urban driving conditions. US06 comprises intrusive, high speed and high acceleration driving approach, speed fluctuations, and start-up after transient parking [19]. ADS represent very swift acceleration from zero to maximum load capacity. This helps to study the rapid heating of the surface mount on FC stack at extreme loading conditions.

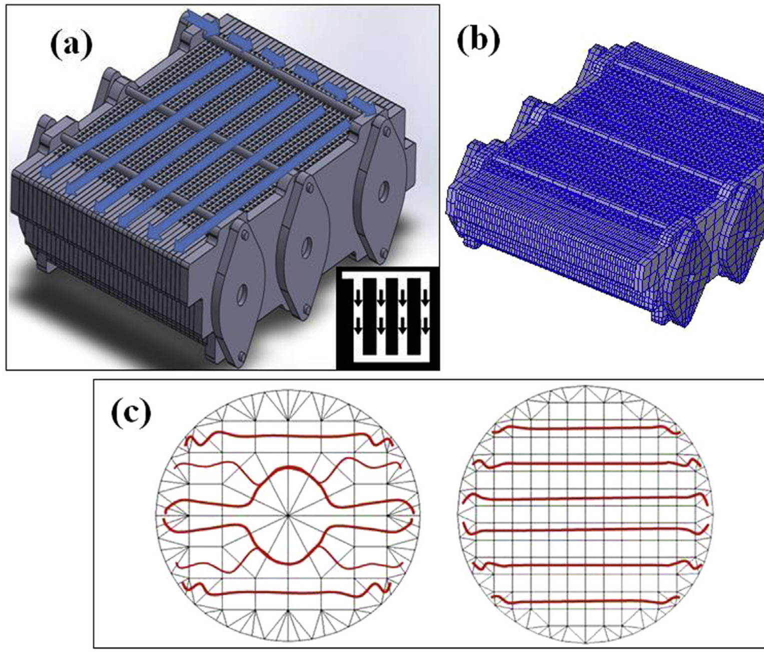

Fig. 2 – 1.2 kW PEMFC stack showing (a) fluid streams, (b) model with meshing and (c) centroid based calculation for FDC.

3D model design

RadTherm (ThermoAnalytics Inc.) is the FDC, which is used for thermal modeling and dissection [20,21]. FDC consists of a functional thermal resolver, which helps in efficient analysis of 3D models. An FDC technique is used due the fact that it is an eminent solver of 3D with surface representation meshed models [22]. Moreover, FDC is the most efficient and popular for heat transfer models with irregular 3D curvilinear meshes [16]. In FDC, the generated 3D model is designated with the attributes for each of elements or cluster having same thermal attributes with thickness, emissivity, flow rates, direction of flow contrast to time curves.

Fig. 2a reveals the 3D model of the FC stack with the flow fields. The Flow pattern for the model is to be assumed as parallel, where inlet is partitioned into 36 flow channels following parallel flow design. Material properties, surface conditions, initial temperature were established for each cell and also other parts of the system. Fluid streams for inlet hydrogen, intake air, stack cooling fan speed were assigned and ringed with its connected geometrical parts. Fluid nodes were initiated to link the fluid stream inlet to split into the channels for each cell. The cooling fan mechanism determines the corresponding cooling and inlet air mass flow rate; with the intake air quality is combined with the chamber surrounding. Similarly, fluid nodes were created for air inlet to

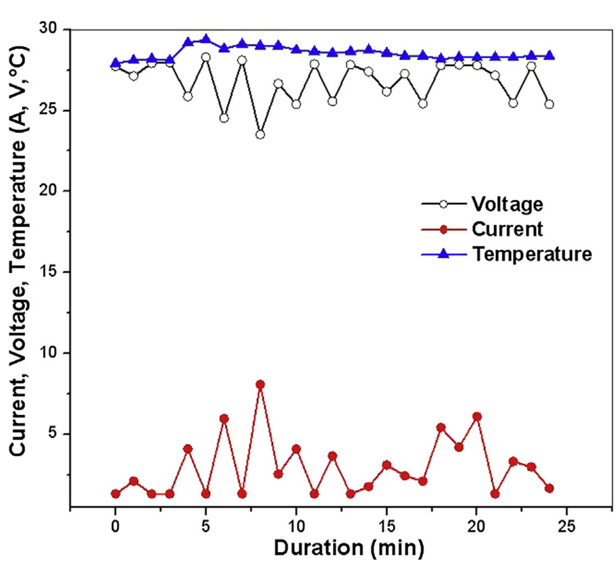

Fig. 3 – PEMFC stack (bottom) temperature and performance characteristics under FUDS test.

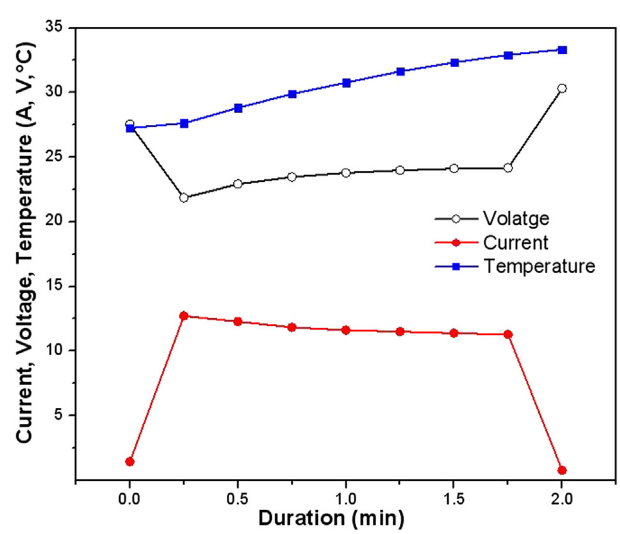

Fig. 4 – PEMFC stack (bottom) temperature and performance characteristics under acceleration test.

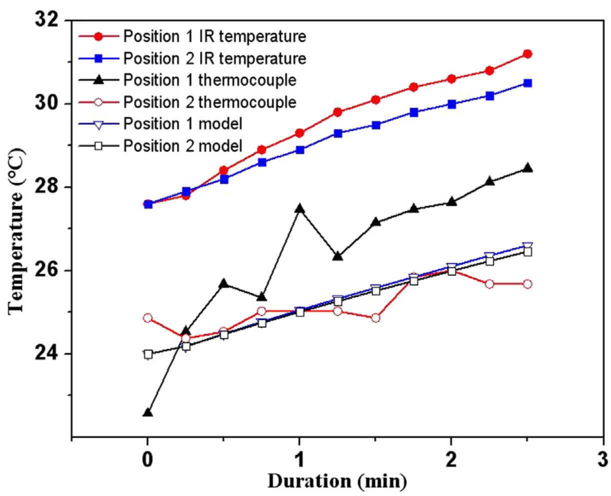

Fig. 5 – Surface Temperature of PEMFC stack at two temperature sensing positions as predicted by IR detector, thermocouples and the model.

connect the model front side with ambient air through the cells, in a way to fabricate forced convective heat transfer between the stack flow field and the ambient air. The created fluid node is linked with every cell in 36 cells stack, to replicate the fluid inside the stack as shown in Fig. 2a. Temperature curves obtained from two pre-positioned thermocouples are also designated to a fluid node within each cell. A set of thermal links are created for all the series connected cells in the stack. The solver is run for each drive cycle sequentially, to replicate the heat transfer for the FC components. The simulated results are also compared with the thermal images obtained from the FLIR camera.

Mesh criteria

Meshing is a process of discretizing a surface into several smooth surface polygons. For FDC purposes, triangles and rectangles are preferred. Quality, size and skewness of meshes of the 3D geometry are the critical steps in simulating the 3D models in the FDC thermal solver. FDC corresponds to give better results with respect to the quality of the mesh. This is due to the fact that FDC assumes a centroid based calculation for the thermal analysis. Fig. 2b explains the model of fuel cell stack after meshing. Fig. 2c illustrates an example of centroid based calculation. The recommended mesh size is 5–25 mm or larger depending upon the geometry model needs as shown in Fig. 2c. However, smaller quality meshes can be done but the computational time increases [23].

Results and discussion

The drive cycle tests were conducted in order to obtain the thermal performance under controlled conditions such as load, temperature, current and voltage. In addition, the tests help arriving at the decisive boundary conditions for the FD duplication of the fuel cell model. The FC system is known to display thermal signature when it is operated under load. The results retrieved include: voltage, current, flow rates of hydrogen and air and actual surface temperature of the fuel cell as recorded by IR camera and the thermocouple as well. Fig. 3 manifests the results encountered during the FUDS drive cycle, depicting that the fuel cell performance parameters (voltage, current and temperature) change significantly. It has been noticed that the surface temperature of the fuel cell increases from 27.6 to 28.4 °C during the FUDS test. Additionally, the acceleration driving schedule validates the steady state performance of the fuel cell system at peak power demands as illustrated in Fig. 4 The test results represent the surface temperature and the current flow at different vehicle speed intervals. It is to be noted that the fuel cell experience a steep increase in the current drawn.

Simulation results

Once the boundary conditions are established with the help of the available data from the test run, the fuel cell model was run for FHDS, FUDS, US-06 and ADS drive cycles, while the time duration for enforcing the thermal solution was set with respect to the time limit of the drive cycle being simulated with 1 min time step size. The thermal performance of the fuel cell was observed under transient and steady state conditions by measuring two locations on the surfaces of the FC stack (one cell in the middle and another at corner of the FC stack).

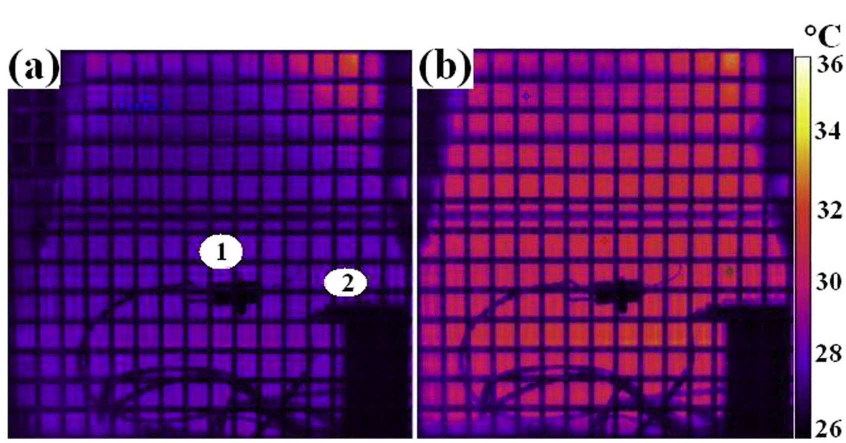

Fig. 6 – 2D thermal images showing temperature profile across the PEMFC stack (a) at the beginning (b) at the end of 12 min.

Table 1 – Temperature values across the thermal images.

Statistic	Image	Temperature sensing 1	Temperature sensing 2
Mean Temperature (start of test)	26.68	27.66	27.67
Mean Temperature (end of test)	27.34	31.21	30.53

Fig. 5 illustrates the temperature of the FC model after simulation in finite differencing code. The figure also depicts correlation of the temperature for the selected positions on the stack as recorded by the stations OEM thermocouples, the average surface temperature as gathered by the infrared camera. The model prediction is done for ADS. It is discerned that the temperature recorded by the IR camera is less than that sensed by the thermocouples. This is due to fact that the thermocouples detect the temperature at the essence of the cells compared to that of the IR detector. Moreover, the excessive cooling air flowing over the surface of the stack might create a slight discrepancy in the reading. From the IR images it is understood that the model is predicting a higher surface temperature on the FC stack.

Fig. 6 depicts a 2D thermal image obtained with the T620 Flir thermal camera illustrating the temperature profile across the FC stack at the beginning and end of the ADS tests. As given in Table 1, the cells at the inner region (temperature sensing 1) showed slightly higher temperature compared to that at the outer region (temperature at position 2) of the FC stack. Conjointly, Fig. 7 exhibits the FC stack heat distribution and surface temperatures at various durations (0, 4, 8 and 12 min) under the FUDS driving test schedule. Such interpretation of the heat distribution helps understanding the thermal loads on the FC stack under implicit conditions, which can be used to assist the fabricator to establish a potent FC stack Thermal Management. Furthermore, it enables us to recuperate the stack packaging composition and identify packaging limitation at an early stage of design process. It is also noted that the temperature gradient of the stack is towards the center.

The results obtained can be used to contrive new thermal control scheme for employing new cooling pattern for perfect operation of stack under different various patterns and environmental conditions. As a consequence, this model created a virtual environment which helps the design engineers to modify the design earlier in the development proceeds with

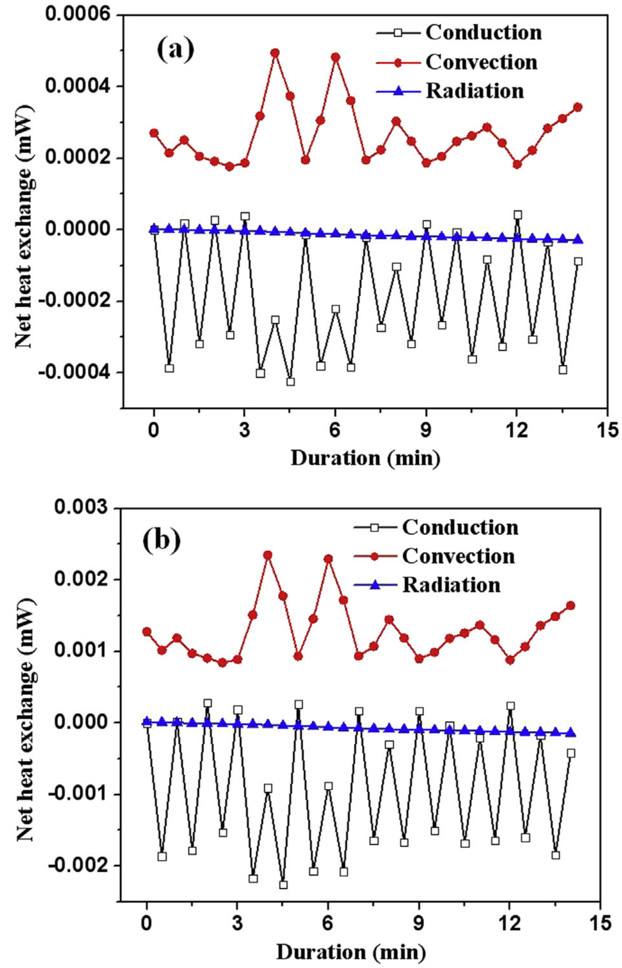

Fig. 8 – Net heat exchange rate by conduction, convection and radiation by temperature sensing at positions (a) 1 and (b) 2.

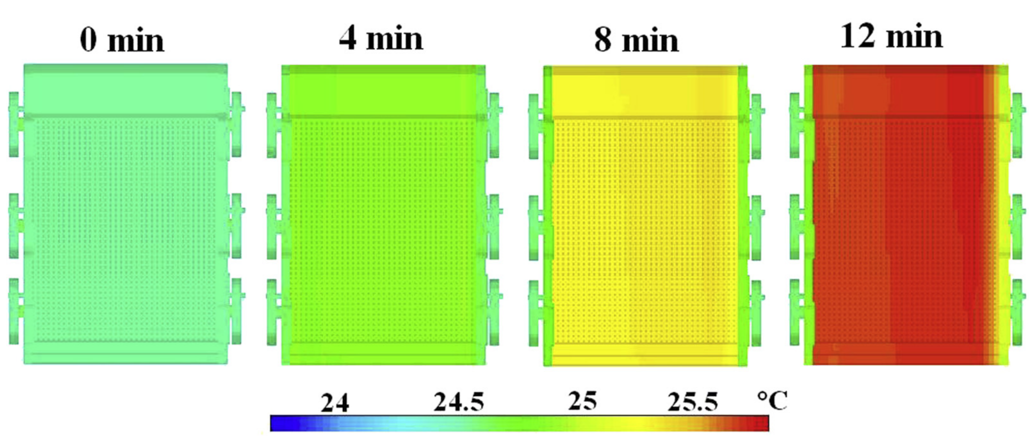

Fig. 7 – Heat distributions and surface temperature for the PEMFC stack under the FUDS driving test schedule for various duration.

less time, cost and effort. Furthermore, the Fuel cell is a proficient model in predicting the net heat exchange rates for geometrical parts and replicating the heat transmission into/out of the different modules. Fig. 8a and b displays the net heat exchange rate for the two pre-selected cells on the FC stack. The figure illustrates the conductive, convective and radiative heat exchange rates for the pre-selected positions on the FC stack. The results obtained can be manipulated to design new and better thermal control strategies for the FC stack.

Interface with thermoelectric module

A thermoelectric cooler (TEC) operates on the Peltier principle of heating or cooling at an electrified junction of two dissimilar conductors [24]. In the current study, Peltier cooling is utilized as a mechanism to control the incoming air temperature. The TEC is considered exceptional cooling technique enforced to thermal operation in PEMFC to cool the bipolar plates [25]. The fuel cell model is compounded with a custom-made TEC system. The system consists of an air duct with internal fins extruding towards the center, and TE modules mounted on the outside of the duct. As electrical current flows through the thermoelectric module, the current-induced phonon transport in the "π-junctions" in the module allows for heat to be removed from one surface (the cold-side) of the TE module, and ejected through the other (the hot side). The hot-side of TE module in this system is attached with fan to allow removal of heat ejected from the module, while its cold-side is mounted on the outside of the cooling duct to allow removal of heat from the fins as illustrated in Fig. 9a. As the incoming air flows through the fins, it cools down by losing heat to the fins. Since the duct with internal fins is an integral part of the thermoelectric cooling system, the design and selection are very important. The system also includes an air temperature sensor and a temperature control loop to maintain optimal air temperature.

This model is tested for the ADS, as this drive cycle manifests greater thermal signature. It is noted that the temperature on the surface of the stack is lowered after the application of the thermo-electric cooler. Furthermore, the temperature of the incoming air is not reduced too much, as it affects the performance of the fuel cell. The TE model is tested for the ADS driving test, as this shows the maximum thermal signature. Fig. 9b demonstrates the application of thermoelectric modules to the model. The TE model is enforced in the differencing code simulator, the united effects of input heat to the hot side like the air flow and temperature, the output flow from the cold source, and the effective heat exchange competency of the sources can be comprehended in the single solver (RadTherm).

As the power is drawn from the FC system, the heat flux across the stack increases. The incoming air passes through the aluminum fins in the duct. The fin is the cold junction of the TE module. The air is cooled by removing the heat and passed to the hot junction of the TE module, which is dissipated from the hot side. It is important that the air is not cooled too much; as it directly affects the performance of the FC system. The main advantage of using a TE module is that, the above principle can be reversed such that the incoming air

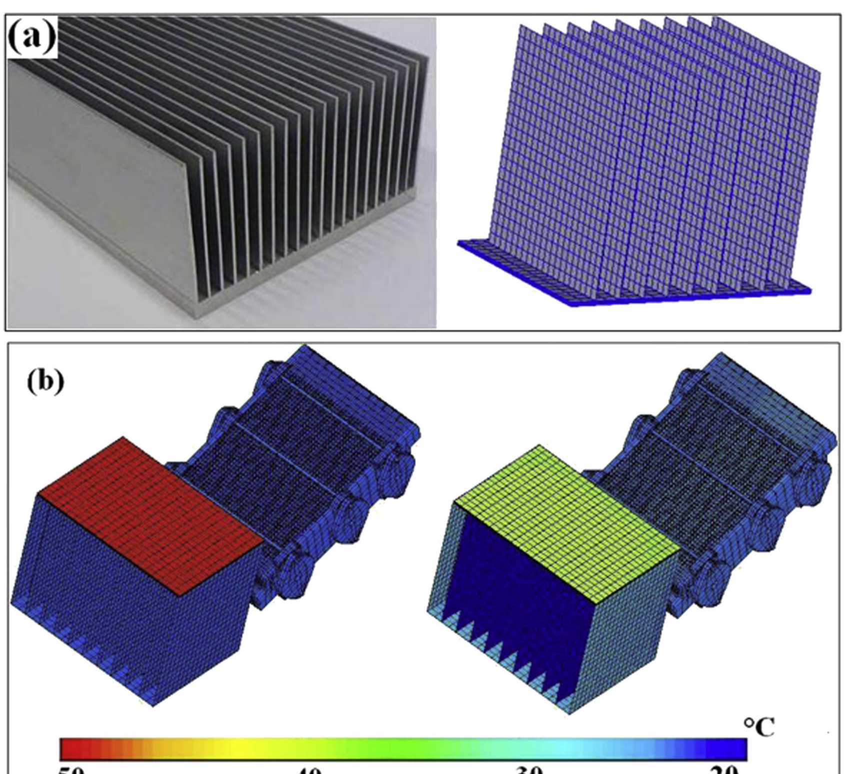

Fig. 9 – Thermoelectric module showing (a) with fins (b) Heat flux at the end of the ADS driving test as anticipated by the model.

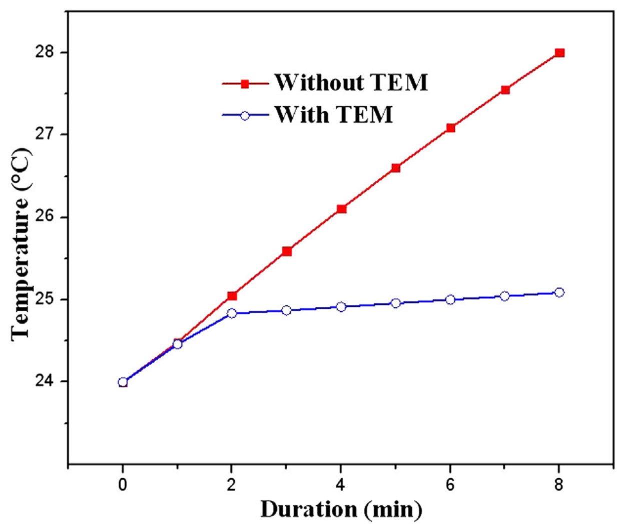

Fig. 10 – Surface temperature curves of the model with and without thermoelectric modules.

can be also heated up especially for cold start-up. The TE module can be optimized and interfaced with the control system of the FC. This enables for efficient cooling based on load requirements.

Fig. 10 shows the average surface temperature across the FC stack with and without the TE modules, respectively. As the graph shows, the TE module enables to control the temperature across the stack within the operating range, such that the performance is unaffected. At around 2 min of operation, there is a sharp rise in current as per ADS driving test. The temperature of the incoming air on the cold side is reduced by heat removal. This maintains the temperature across the surface of the stack according to current drawn the stack, illustrating the control strategy instilled with the TE module.

The starting hot side is at 50 °C for ambient temperature of 23 °C is maintained. As the power drawn from the stack increases, the heat from inlet air passes to hot side from the cold side. The amount of heat load needed to remove and the desired cold-side temperature, enables to determine input voltage. The interfaced module is capable of producing 10 °C temperature difference (ΔT) when induced with open circuit voltage of 3.3 V. It is also noted that the temperature on the cold side is decreased by around 3–4 °C, this may be due to fact that there is a reduction in temperature on the hot-side [26].

Conclusion

The proposed work examines the augmentation of a 3D thermal model of a PEM FC stack. The Model is forged and justified for system running in HiL under different standard and user-defined driving schedules. The 3D thermal model is refined using a FDC integrated with experimentally extracted boundary conditions including electric current, power, flow rates and temperature curves. The spatial and temporal temperature profiles of the proposed model reconcile with that of the experimental data of the FC stack as provided by the control unit of the FC. The solutions obtained show that the model is capable of predicting the thermal behavior of the fuel cell under controlled scheme (load, power, temperature and environmental conditions). Furthermore, an analysis is conducted to evaluate the incident heat exchange rates by conduction, convection and radiation. A scheme of simulation and optimization for a TE module has been contemplated based on the proposed modeling. The TE model of the inlet duct has been manifested and braced with the TE system model in FDC as a whole. Future research will focus on the effects on entire FC system to achieve optimized system modeling strategy.

Acknowledgments

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Appendix. Flow rates and model parameters

This section discusses the flow rate and the model parameters on the FDC solver. Based on the current drawn, flow rates of hydrogen and air, of the anode and cathode are calculated respectively. Generally, in a FC stack supplied with pure hydrogen, the fuel consumption can be obtained by.

$$m_{H_2} = (1.05 \times 10^{-8})(P_S/V_{FC}) \tag{1}$$

where m_{H_2}, is the hydrogen mass flow rate (kg/s); V_{FC} is the FC voltage (V) and P_S is the stack electrical power (W), obtained from,

$$P_S = n \cdot V_{FC} \cdot i_{FC} \tag{2}$$

where n is the number of cells used on the stack.

The air mass flow rate (kg/s) can be obtained using the equation in 3.

$$m_{air} = (3.57 \times 10^{-7})\lambda(P_S/V_{FC}) \tag{3}$$

where, λ is the stoichiometric rate.

The FDC splits the elements with same properties into thermal nodes. The total radiation exchange between two surfaces which are assigned to different thermal nodes i and j is calculated using the equation (4) [27–29].

$$Q_{ij} = B_{ij} A_i \varepsilon_i \sigma_i \left(T_i^4 - T_j^4\right) \tag{4}$$

where Q – net radiation heat exchange (Watt)

B_{ij} – energy emitted from surface i and absorbed at surface j
A – Area (m^2)
ε_i – emissivity
σ_i – Stefan–Boltzmann constant (Wm^2K^{-4})
T_i, T_j – temperature of objects i and j, respectively (Kelvin)

One of the key factor and advantage of the existent solver is its ability to create thermal nodes while replicating fluid

streams. Though, the solver calculates the temperature nodes based on practical mode, the theoretical way of calculating node temperature is by an energy balancing equation given by Ref. [28].

$$\sum Q^* = m\ C_p\left(dT/dt\right) \quad (5)$$

where Q is heat rate in joules, m is mass in kg, C_p is the specific heat and T is the temperature in K.

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